Ultra-light Vapor Fueled Cavity Reactors with MHD for Powering Multi-Megawatt NEP Systems

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Innovative Nuclear Space Power and Propulsion Institute

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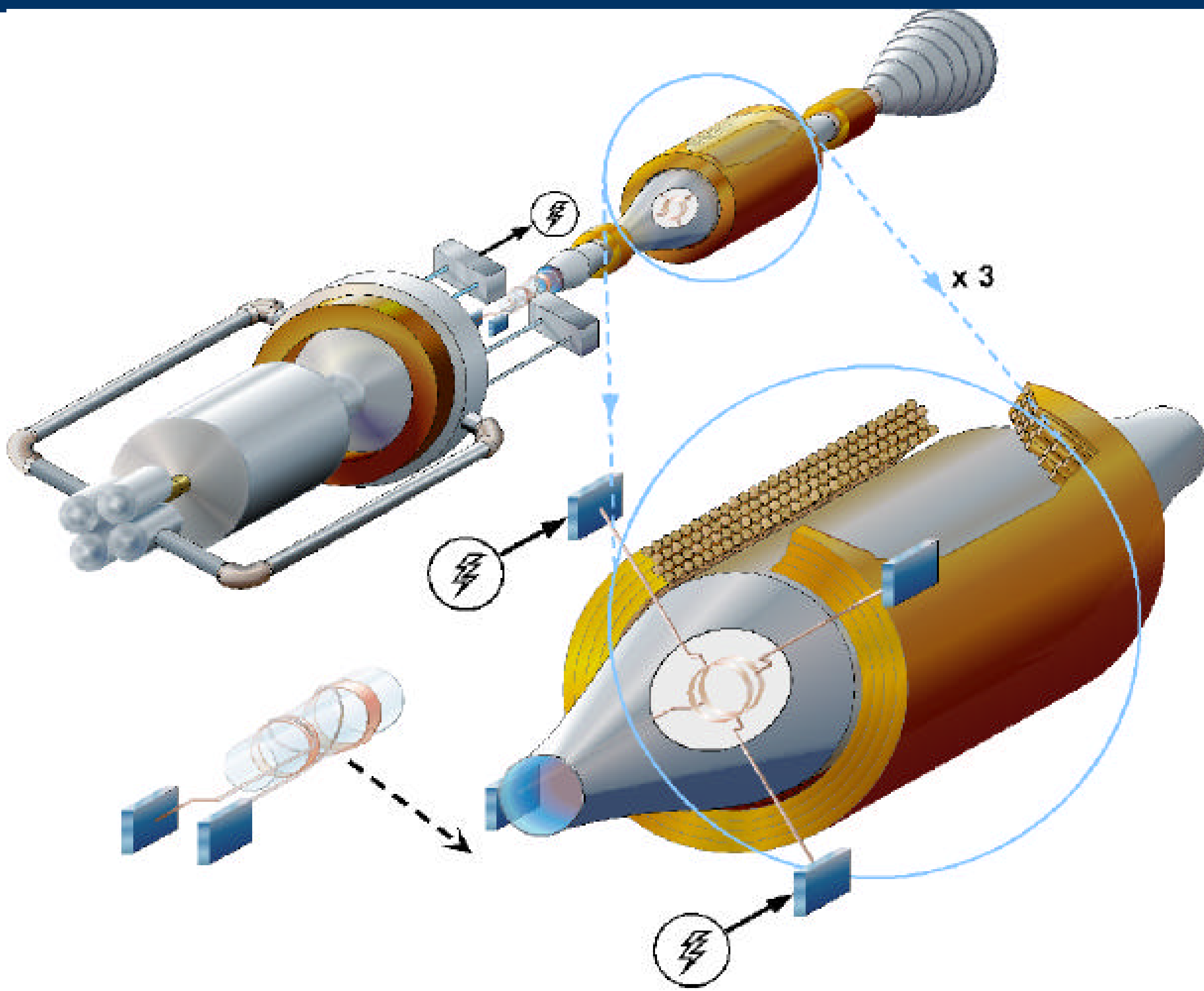
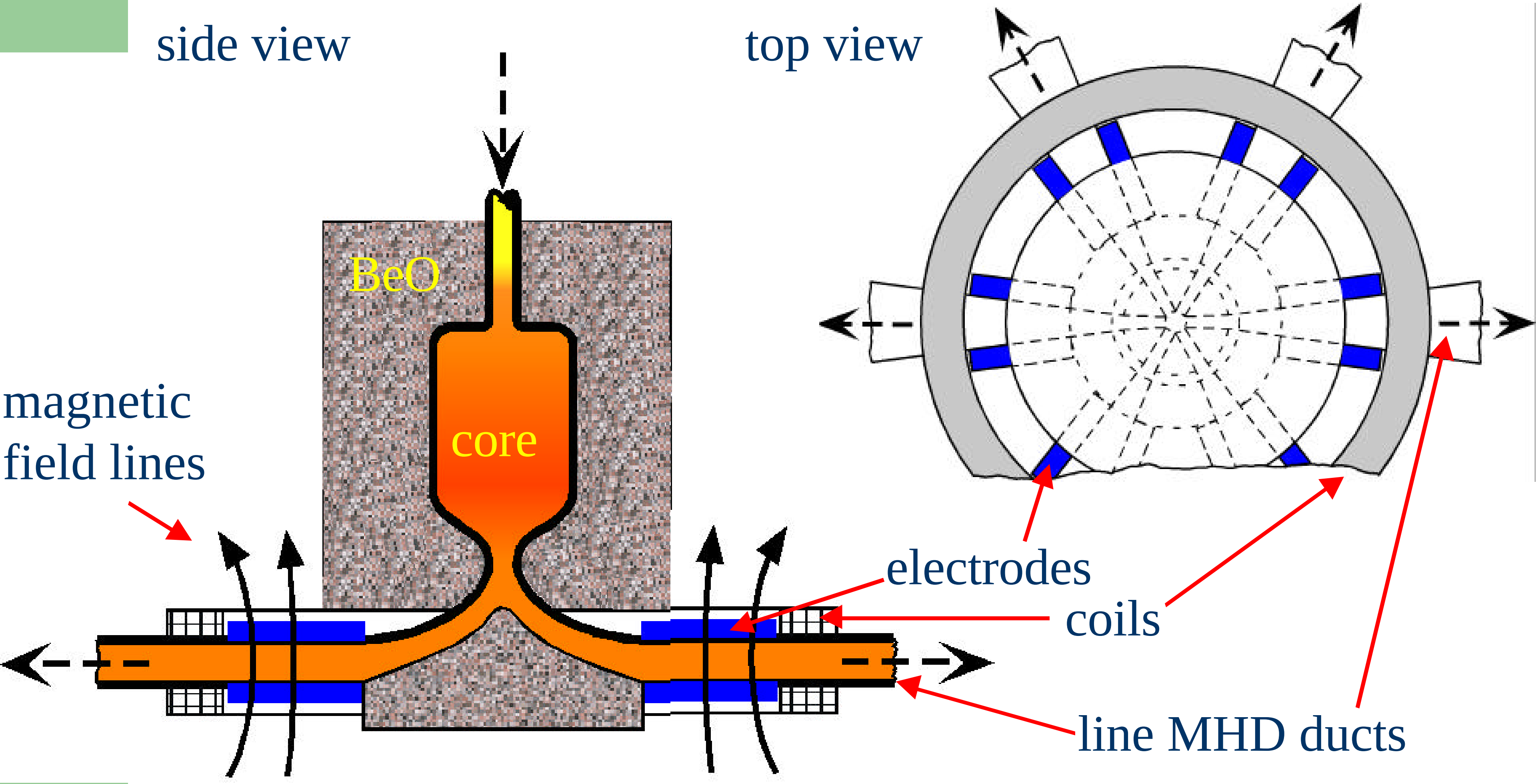
Overview of Nuclear MHD Power Conversion for Multi-MW Propulsion



Fissioning Plasma Core Reactor



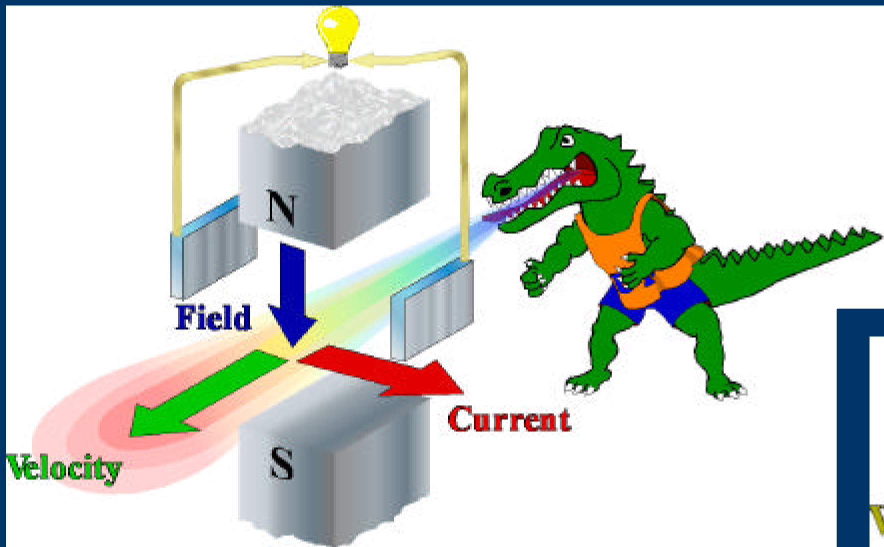
Overview - Fissioning Plasma Core Reactor with MHD (FPCR-MHD)

- Fissioning fuel, UF_4
- Working fluid, alkali metals or their fluorides (K, Li, Na, KF, LiF, NaF, etc.)
- Core Outlet T., 3000 to 4000 K
- Specific mass, 0.4 to 0.6 kg/kWe
- Power, 10 to 200+ MWe
- Coupling to MPD, VASIMR, other thruster
- Isp, 1500 to 10,000 s.

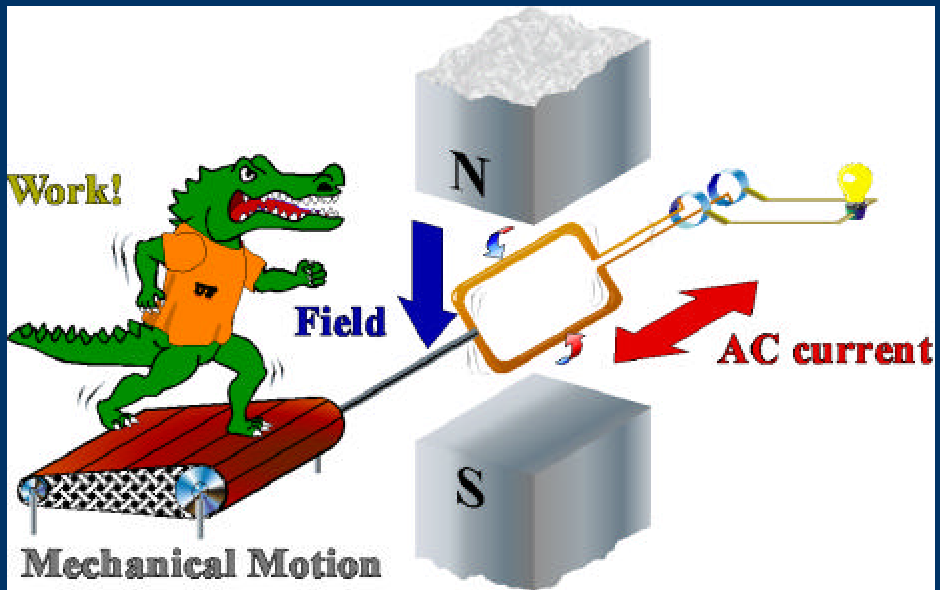
Advantages of Gaseous/Liquid Fuel

- In space assembly, fueling and refueling
- Ultra-safe fuel handling and delivery
- Operating temperature not constrained by fuel melting
  - high efficiency
  - minimizes radiator size/weight
  - no heat transfer barriers between fuel & working fluid
- Power scaling by varying fuel recirculation rate and average fuel exit temperature
- High temperature cavity reactor with integrated containment and moderator/reflector structure as well as integrated fuel/heat transport leading to very low kg/kWe

The Principle of MHD Generators



- MHD generator
  - Only twice downgraded.

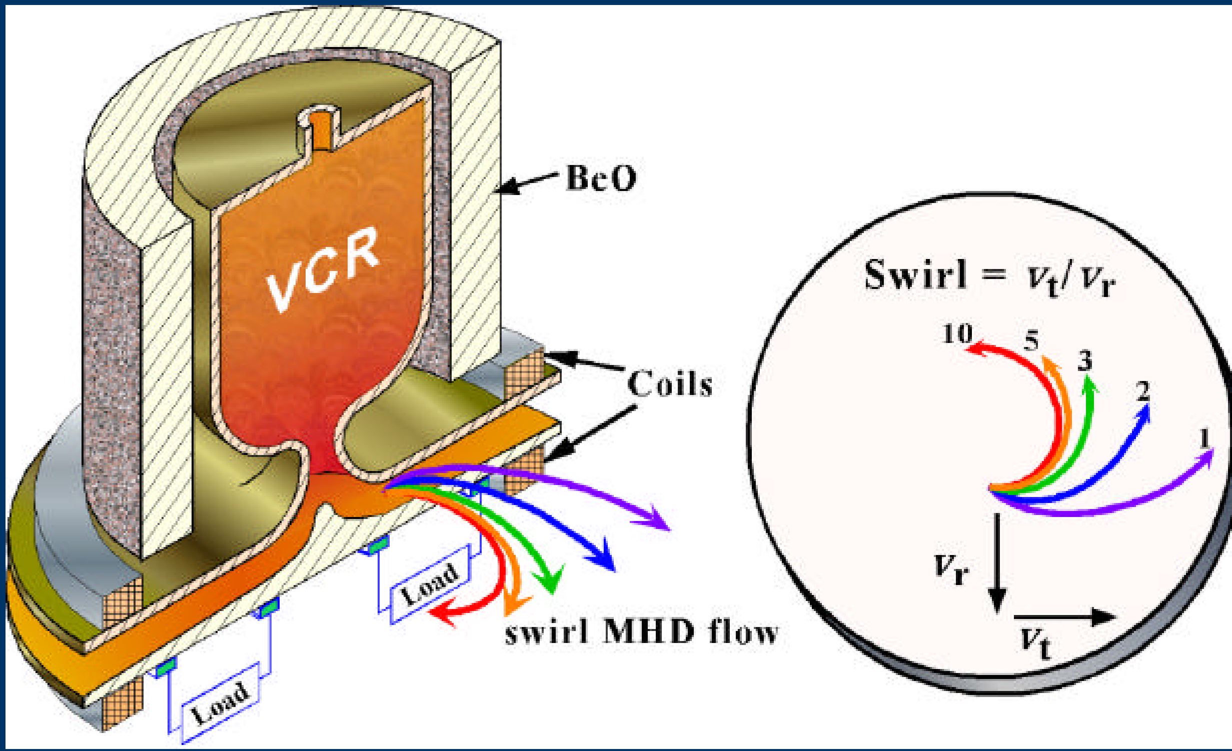


- Steam turbine
  - At least 3 downgrades.

Nuclear MHD Power Generation

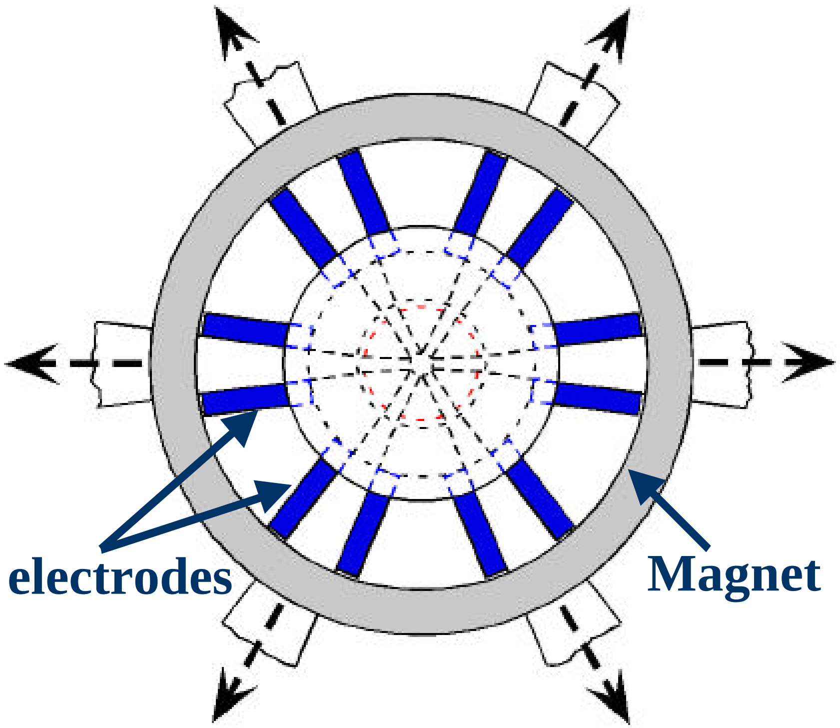
- No moving parts, high temperature cycle
- Utilize energy in its highest quality before degraded to heat
- Enhanced electrical conductivity of working fluid by fission-induced non-equilibrium ionization
- Minimum power conditioning needed – direct coupling with MPD, VASIMR or other thrusters

Disk VCR-MHD Generator

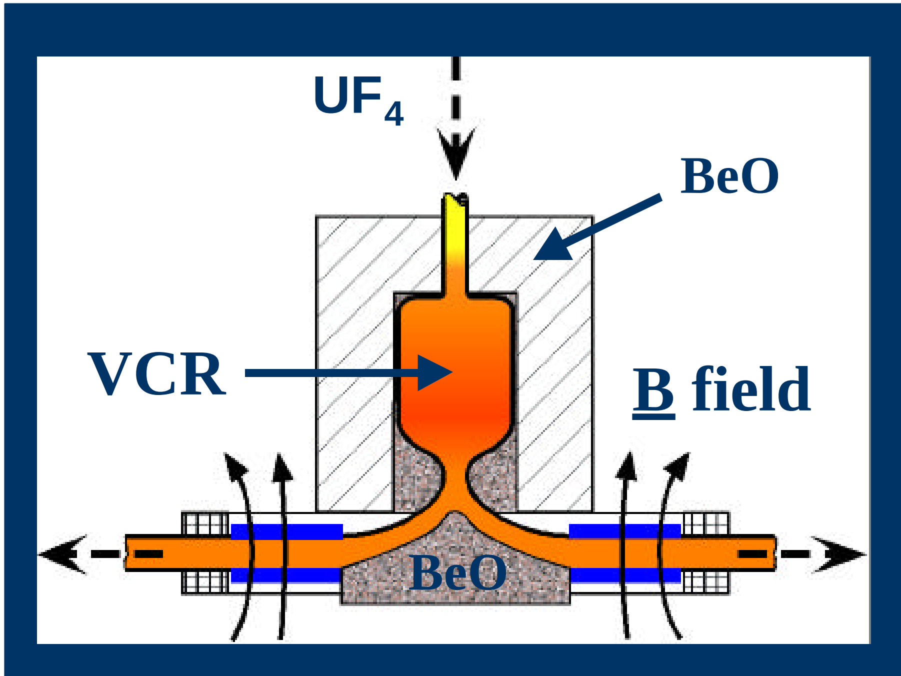


- Hall regime, efficiency increases with $wt = mB$.
- Hall efficiency increases with swirl (ie. tangential velocity).

Radial Line MHD Generator



- Simpler design than disk swirl generator.
- No swirl flow required.



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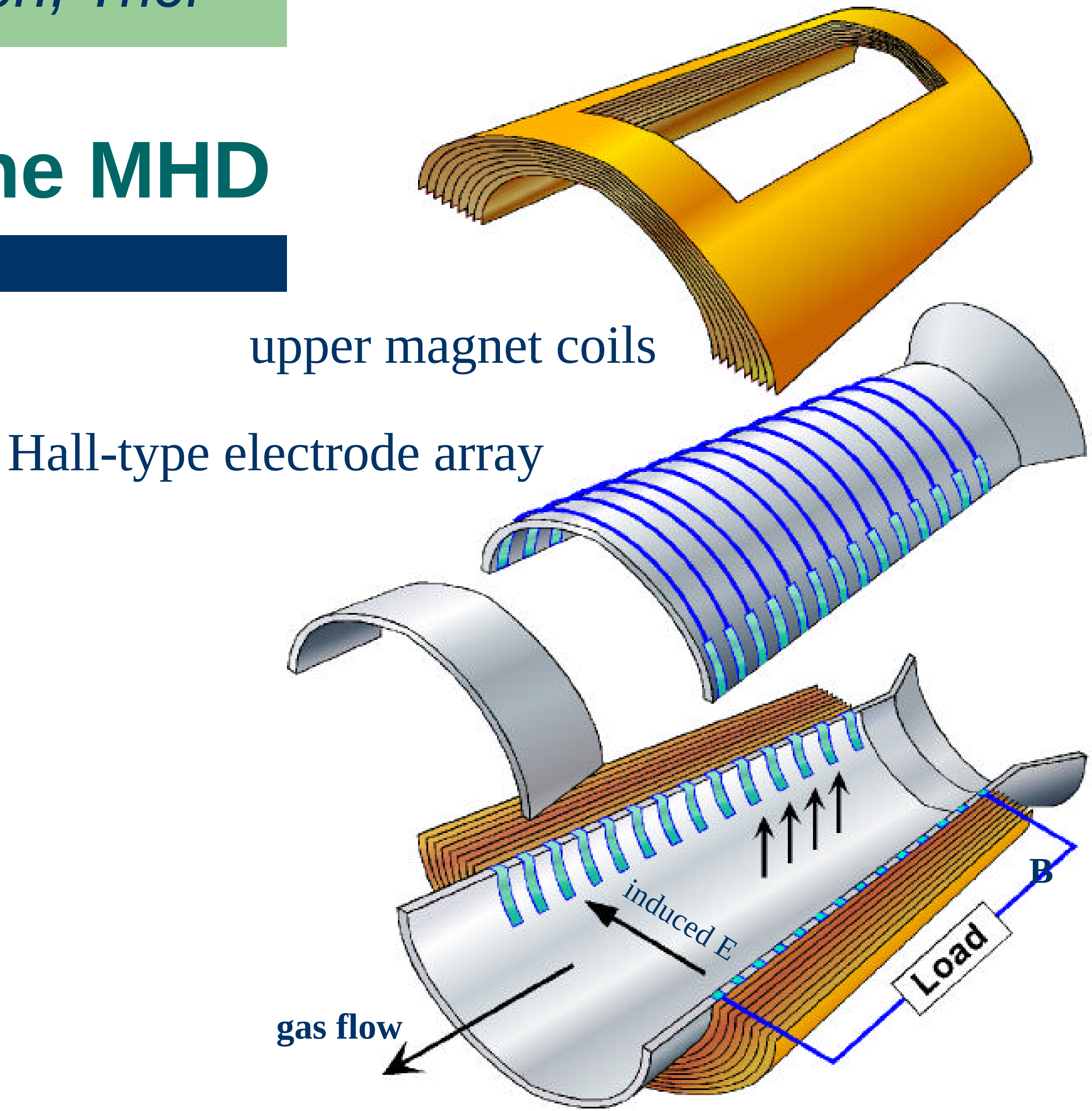
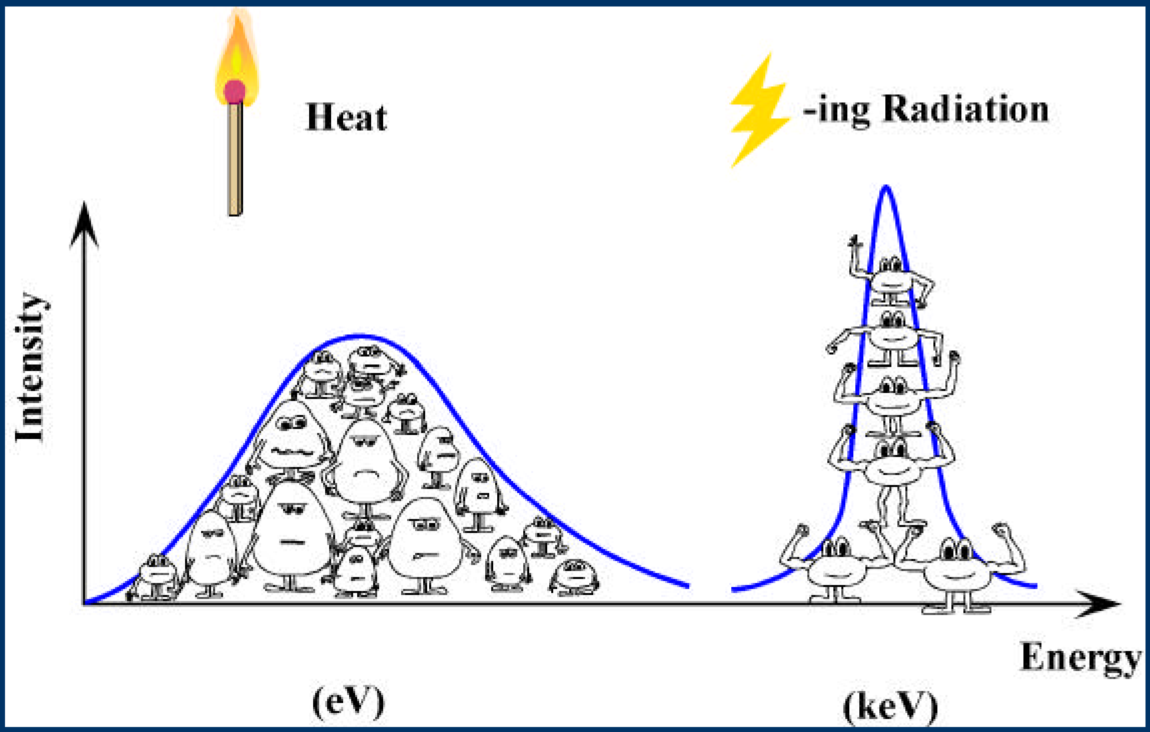
Line MHD



Plasma Electrical Conductivity

- $= ne$
- Losses $\propto n^2$.
- = electric conductivity, n = electron density, = *electron mobility*.
- *MHD Power Density* $= \; v^2 B^2$
- To minimize losses, n should be Low.
- In Nuclear MHD B^2 could be High.

Fission Product Ionization



Fission radiative:
Fewer but "power" workers.

Thermal :
Large number of "lazy" workers.

- Saha equation for thermal ionization, $n_e n_i \sim T^{3/2}\exp(-e/kT)$, gives ~ KeV or less.
- Fission product radiation, average β–energy ~ 900 keV.

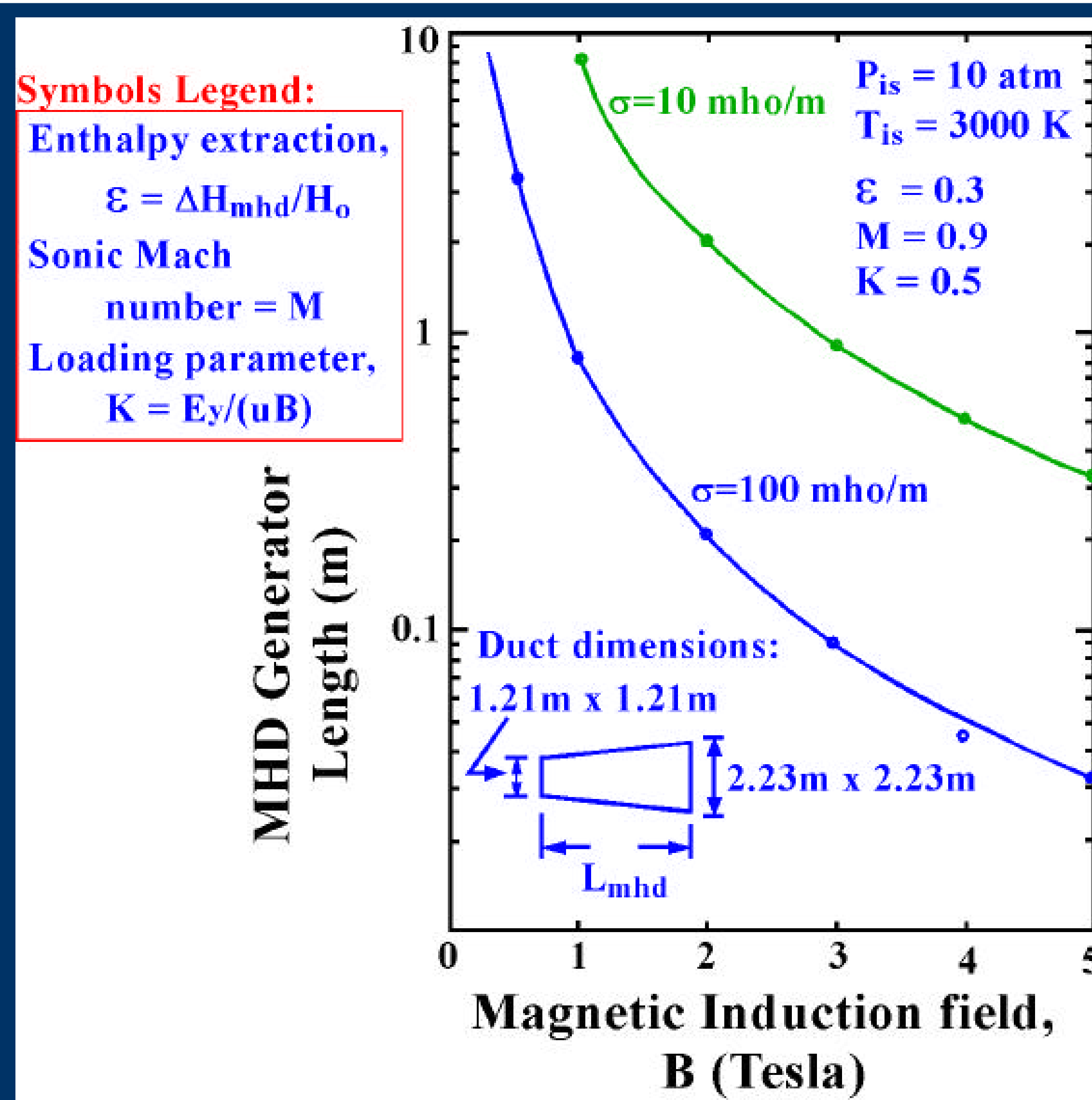
∴ Fission enhanced conductivity, $\sigma \sim T^{3/2}\,\Phi^{1/3}\,T_e$

Some MHD Generator Characteristics

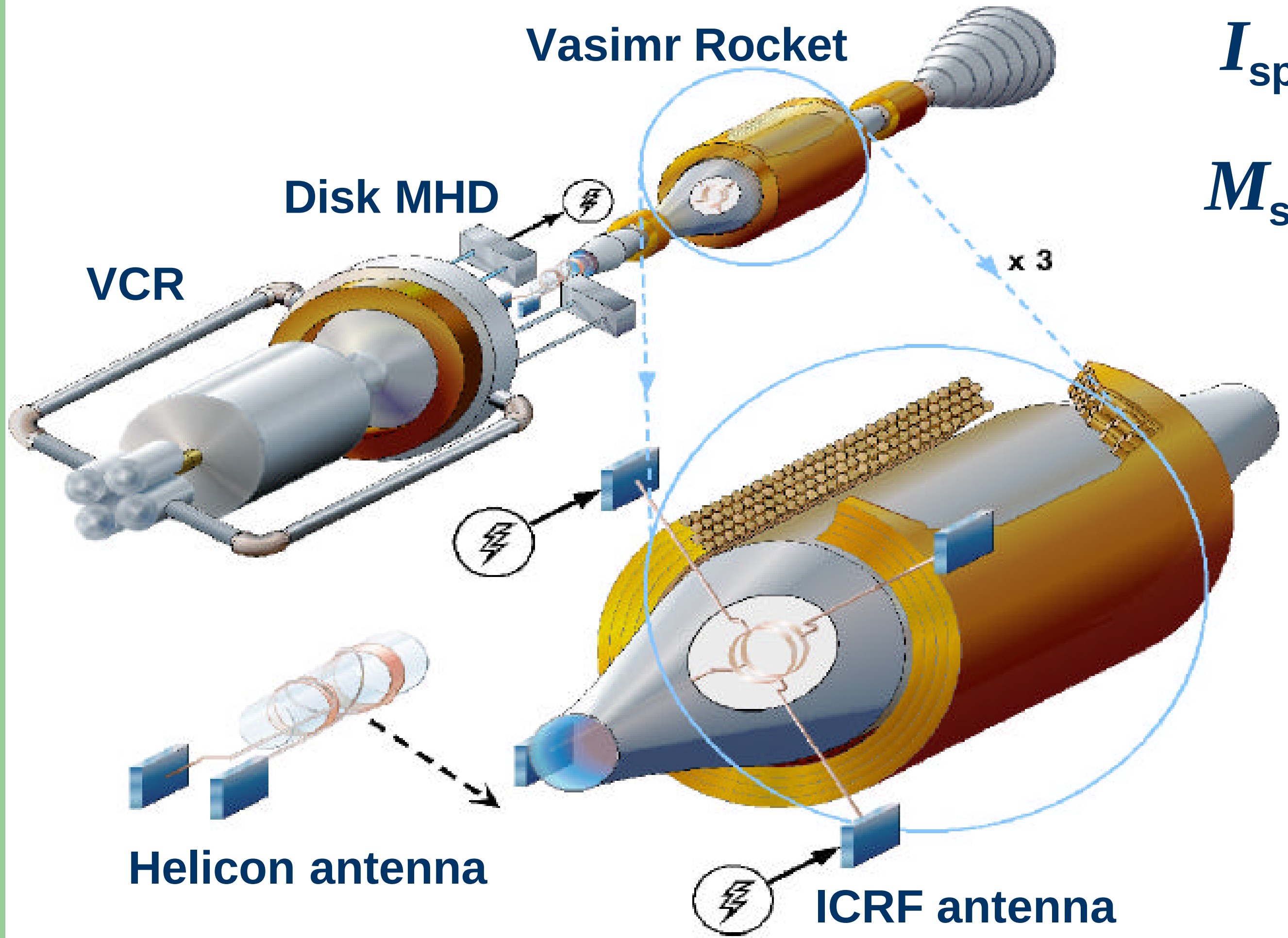
- MHD length

  L = L(s,B).

- -B Þ -s for same L.



Fully Integrated VCR-MHD-VASIMR NEP System

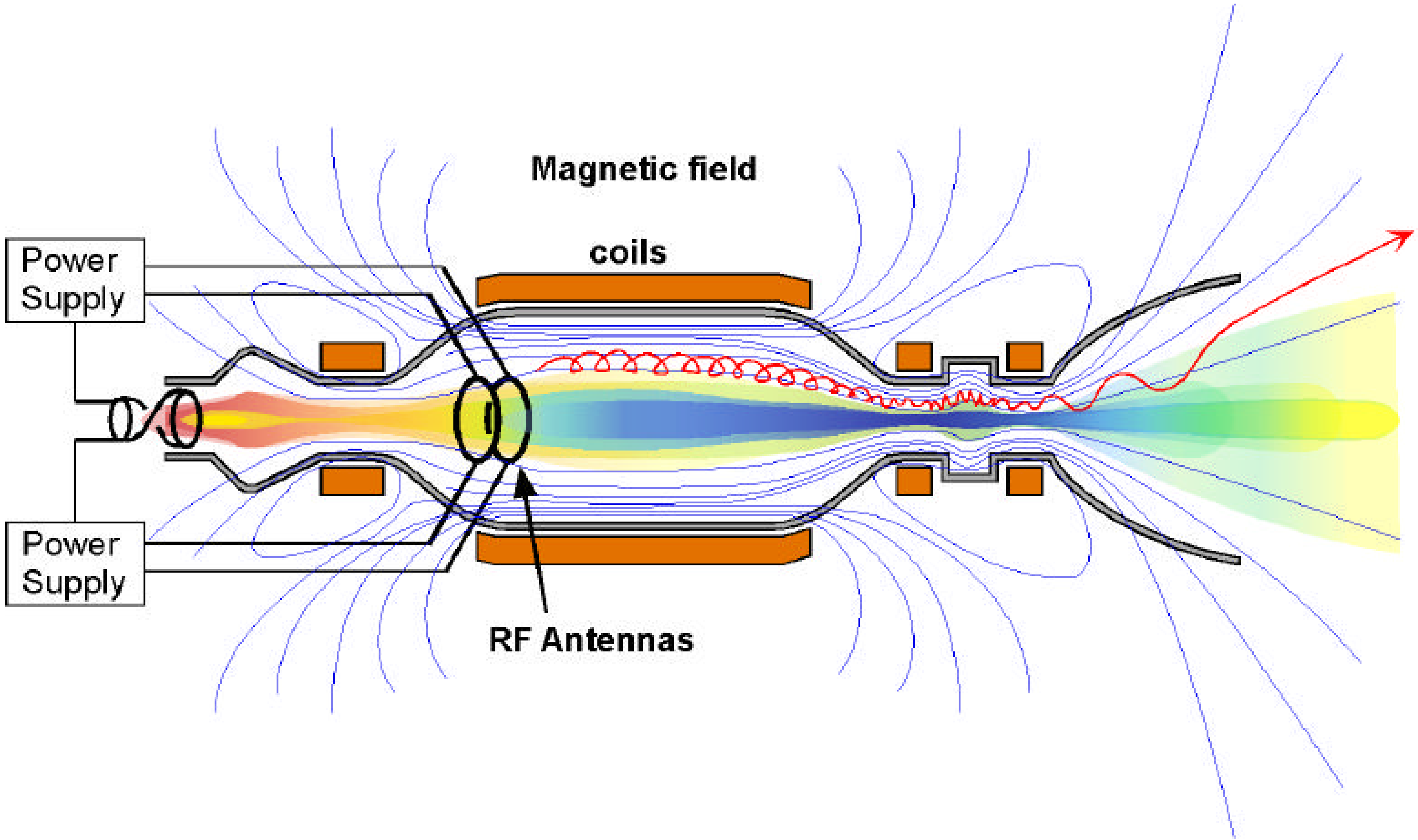


I_{sp} ~ 10,000 s

M_{sp} £ 1.0 kg/kW_e

… Specific Concepts, part 2: *VASIMR*

Variable Specific Impulse Magnetoplasma Rocket



Propulsion using magnetic mirrors in VASIMR.

Nuclear MHD Power and NEP

- High power density in gas core reactors.
- Heat rejection at higher temperature,
  - Size of radiators can be reduced.
- Low specific mass,
  High specific impulse,
  - Meets Mars quick trip requirements.

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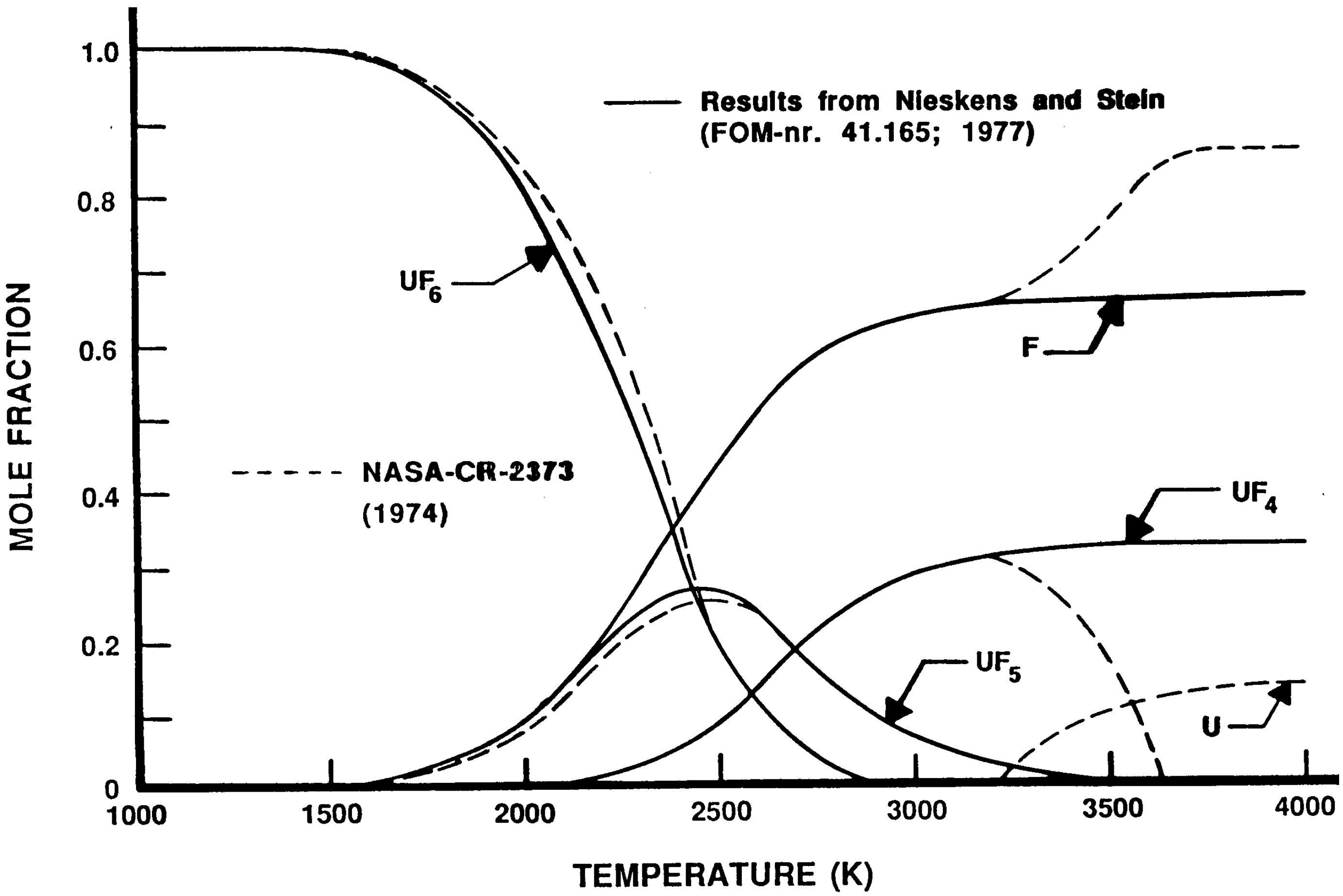
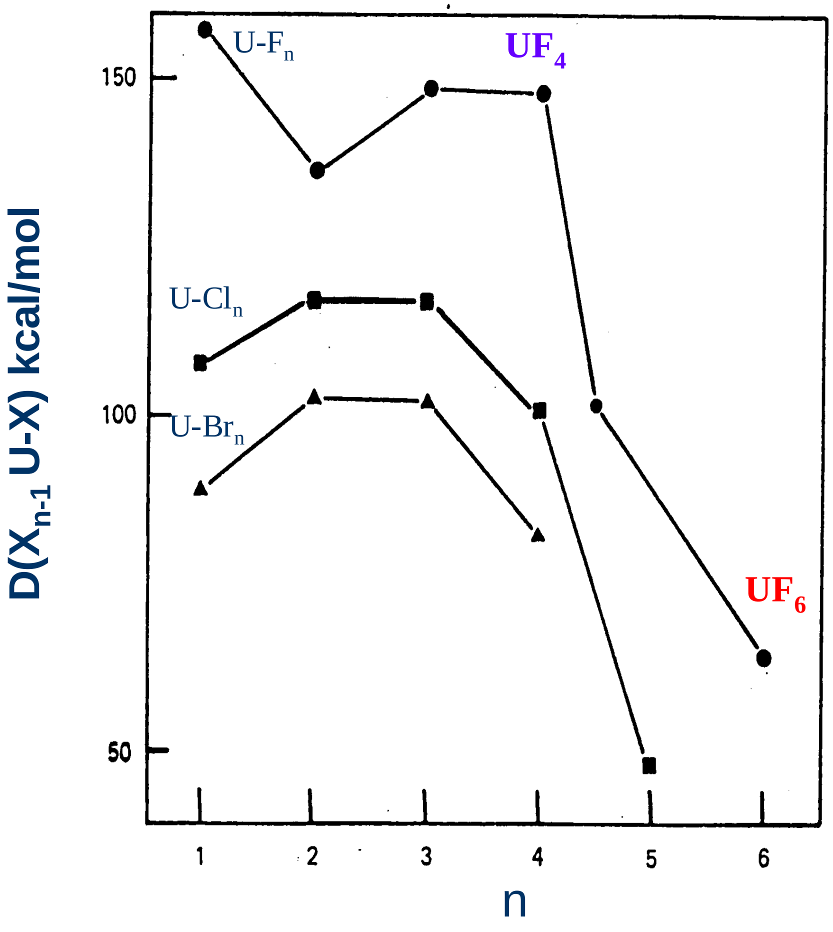
U-F system, UF_4 the most stable uranium compound in liquid and gaseous phase



U-F_n Bond Dissociation Energies



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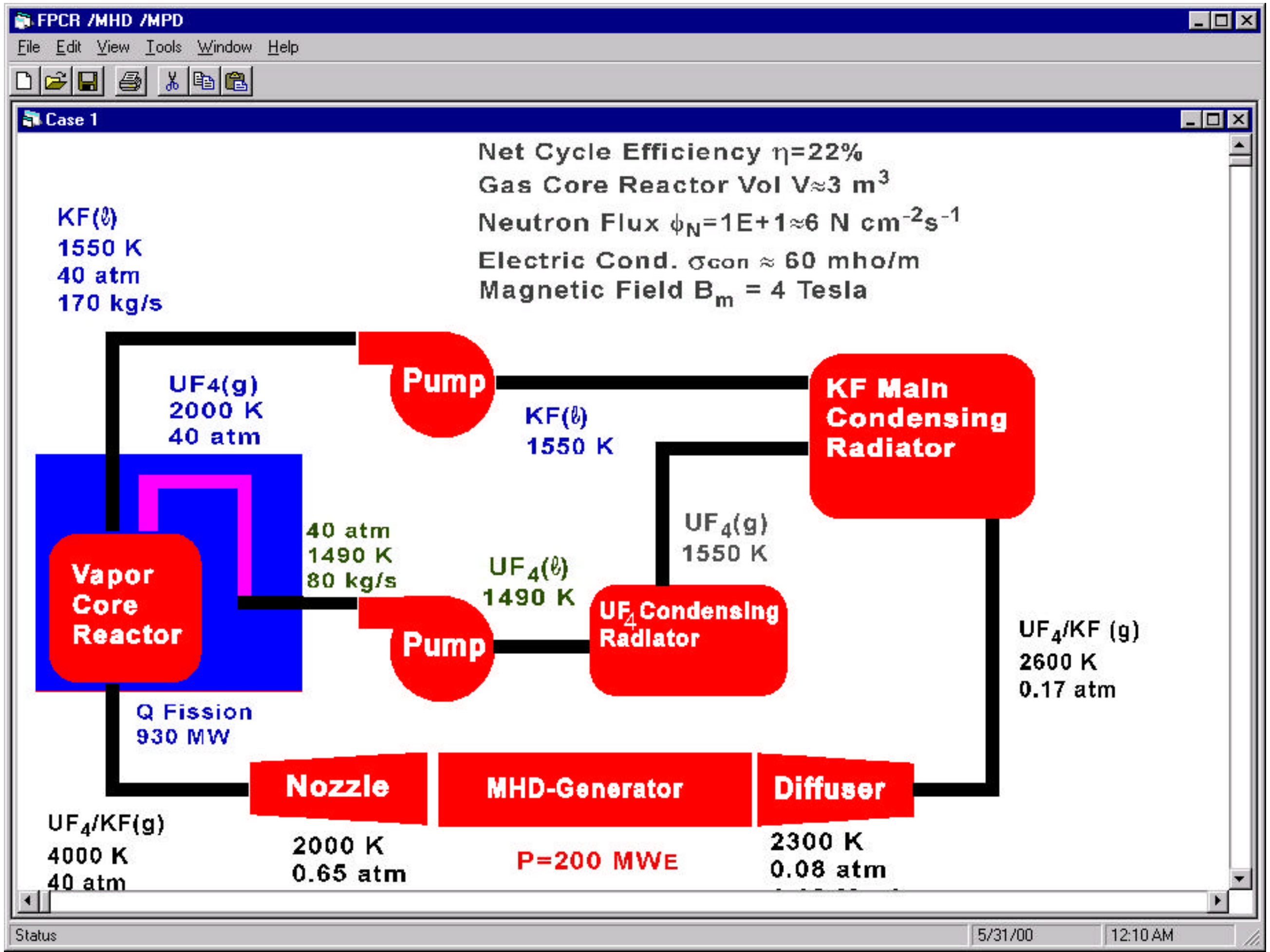
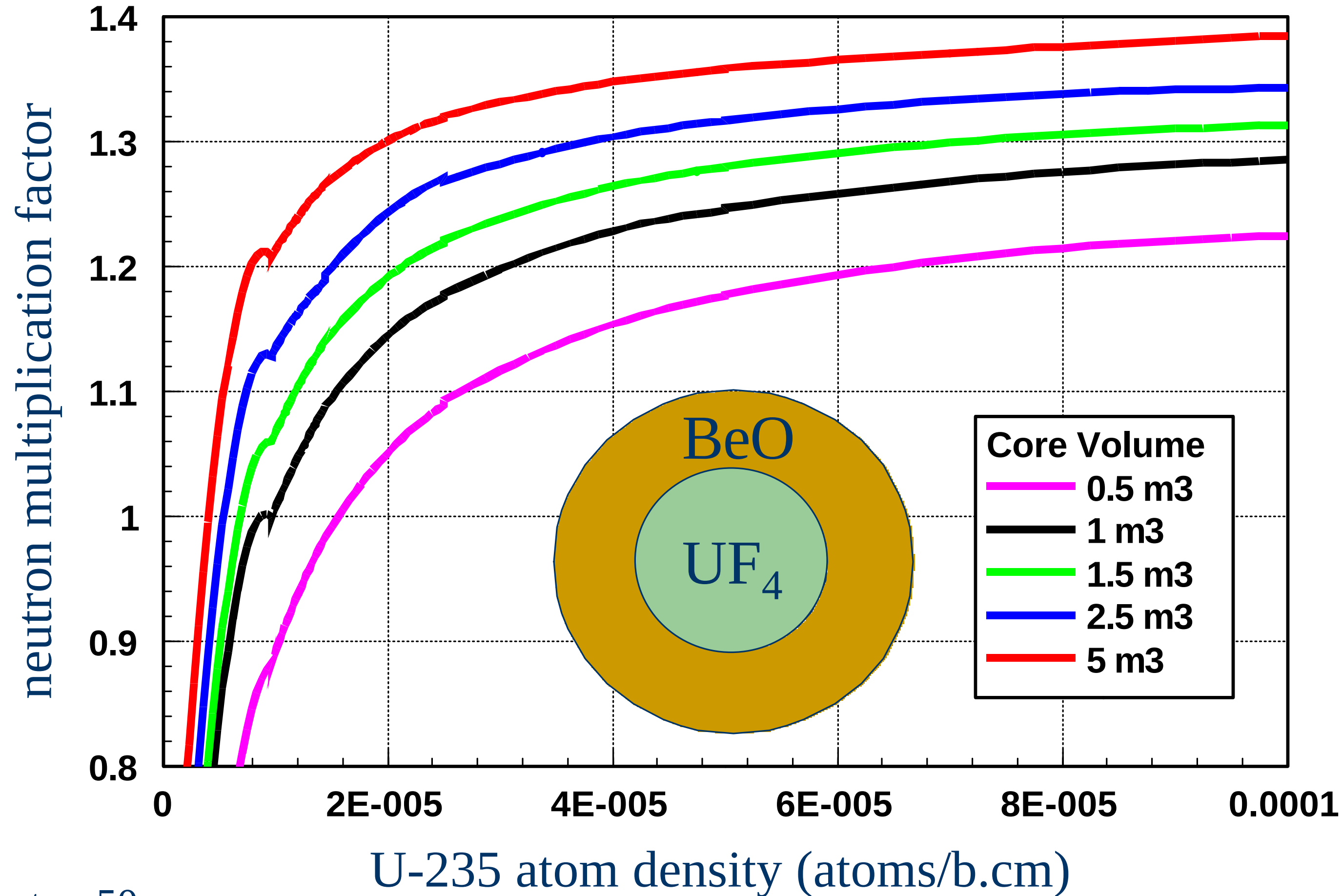
Fissioning Plasma Core Reactor Simulation Code

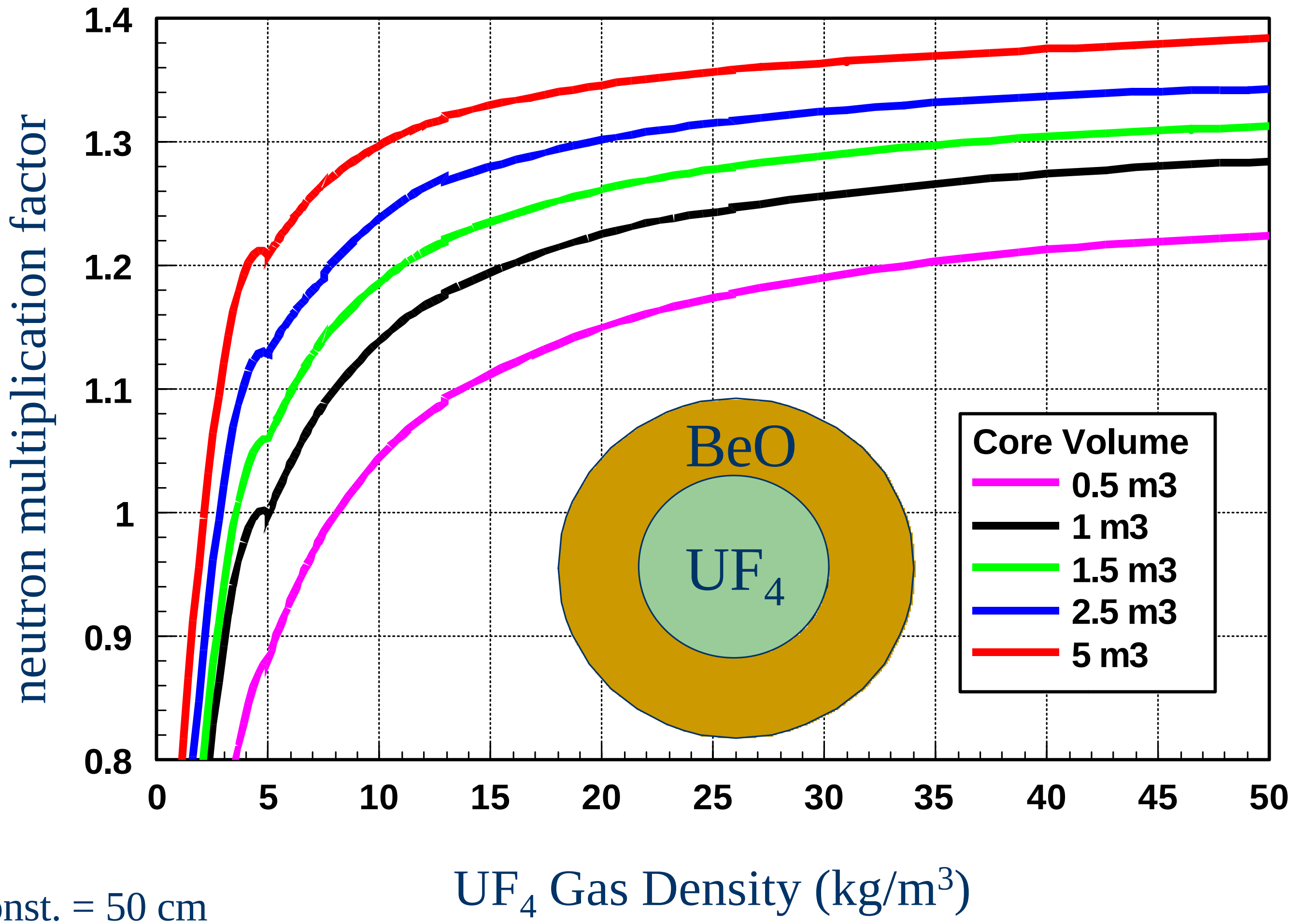


Cavity Reactor – Neutron Multiplication Factor



BeO thickness = const. = 50 cm

Cavity Reactor – Neutron Multiplication Factor



BeO thickness = const. = 50 cm

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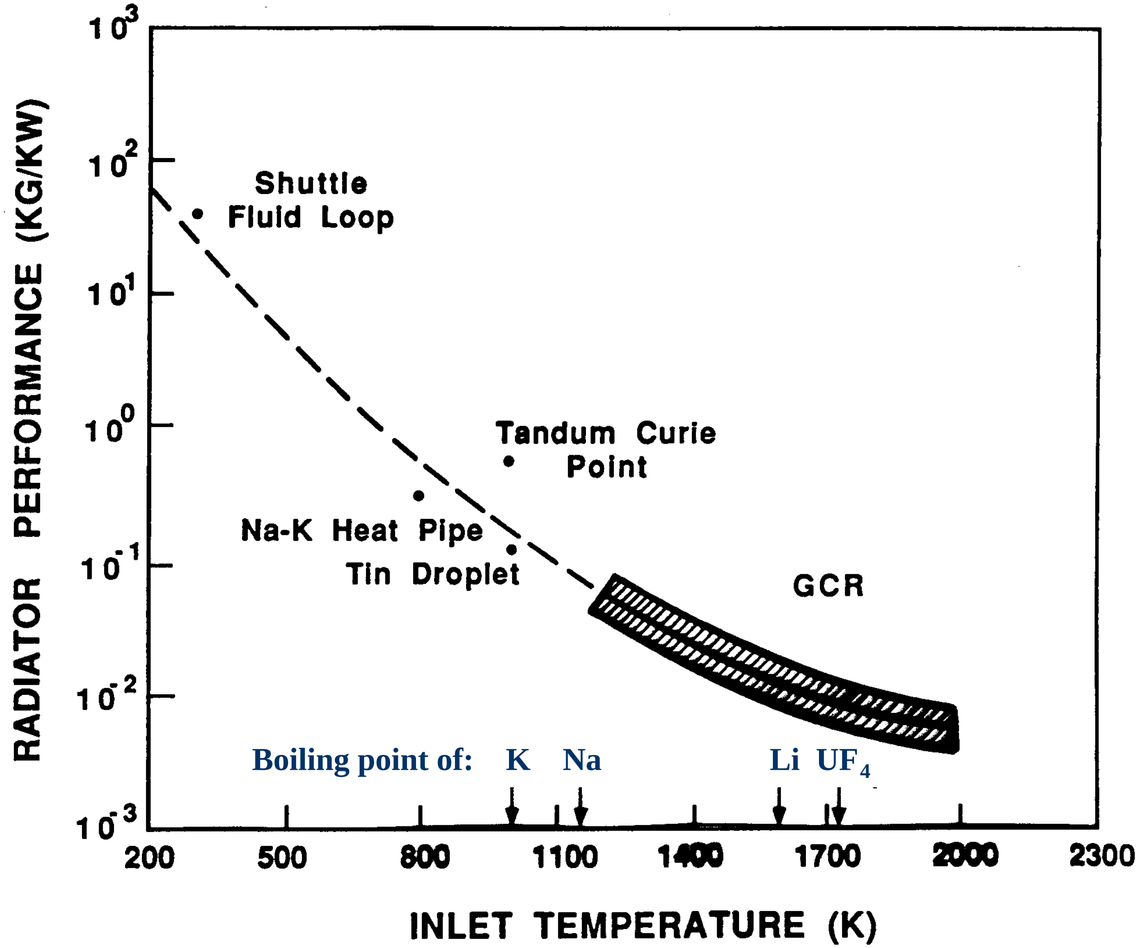
Radiator Mass to Power Ratio



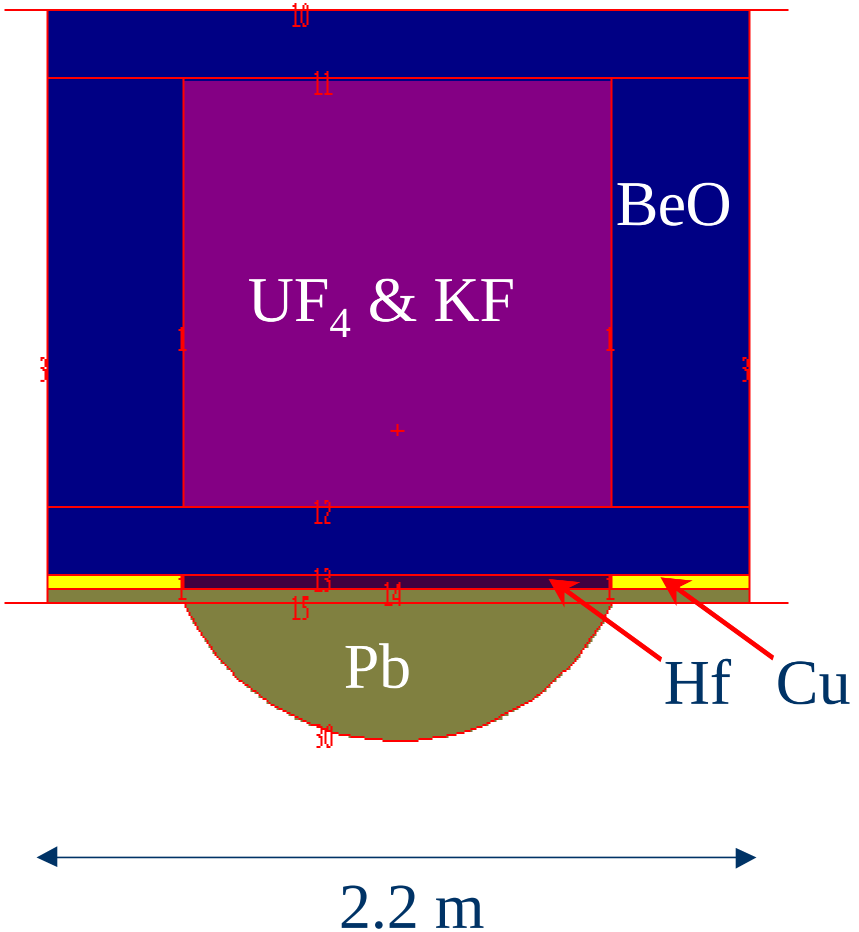
Specific Mass Calculation

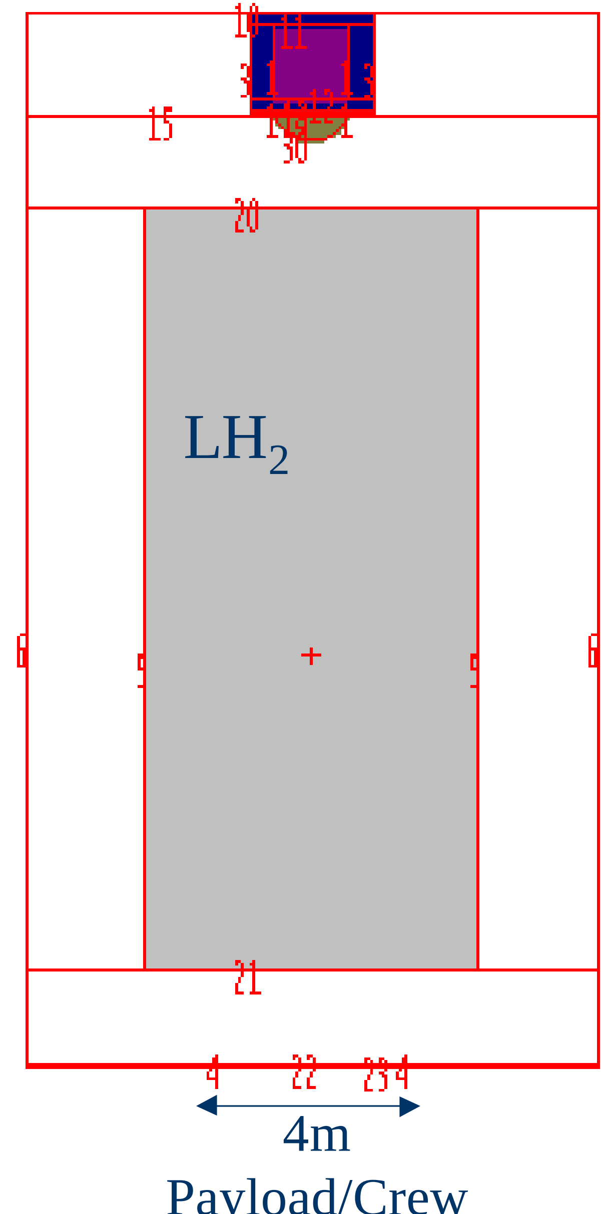
- Core & Reflector
- Reactor Vessel & Structural Materials
  - Stainless steel
  - TZM (Mo99/Ti0.9/Zr0.1), Mo-Ti alloys
  - Ti-Al alloys
- Radiation Shield (Pb,Cu,Hf,polyethylene,B_4C)
- Radiators
- MHD Generator
- Pumps and plumbing

Radiation Shielding Calculation

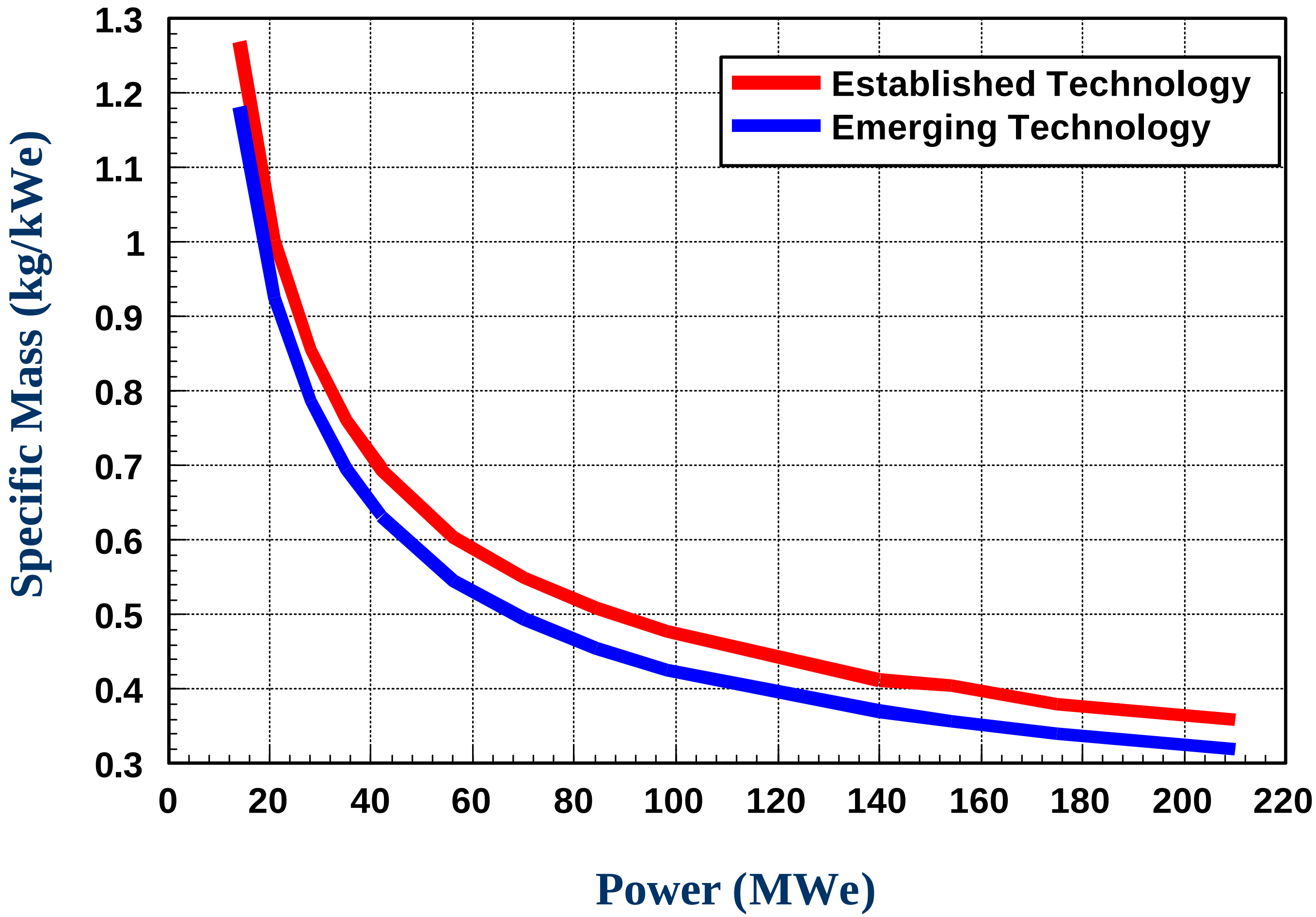
- Laminated Pb/Hf/Cu planar and semi-circular shield with additional polyethylene shielding for crew
- Additional Shielding possible with L H_2 tanks between reactor and payload/crew module (typically 50 MT)
- Sources – neutrons and photons from fission
  - Neutrons – Watt fission spectrum (incl. prompt & delayed)
  - Photons – including prompt & decay ☎ -rays

MCNP Reactor & Shield Model

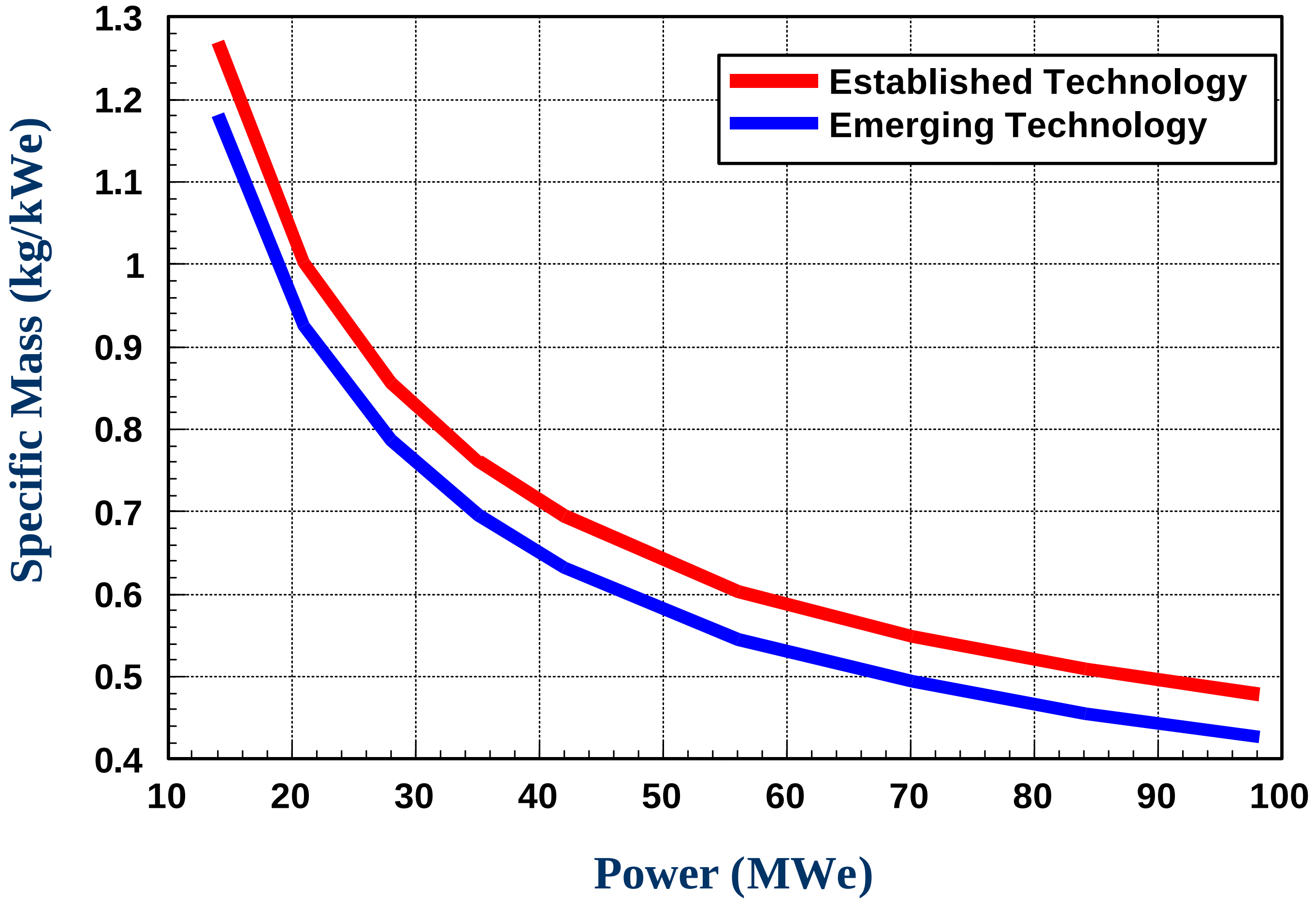




Fissioning Plasma Core Reactor Weight Performance (<1kg/kWe for >20MWe)



Fissioning Plasma Core Reactor Weight Performance (<1kg/kWe for >20MWe)



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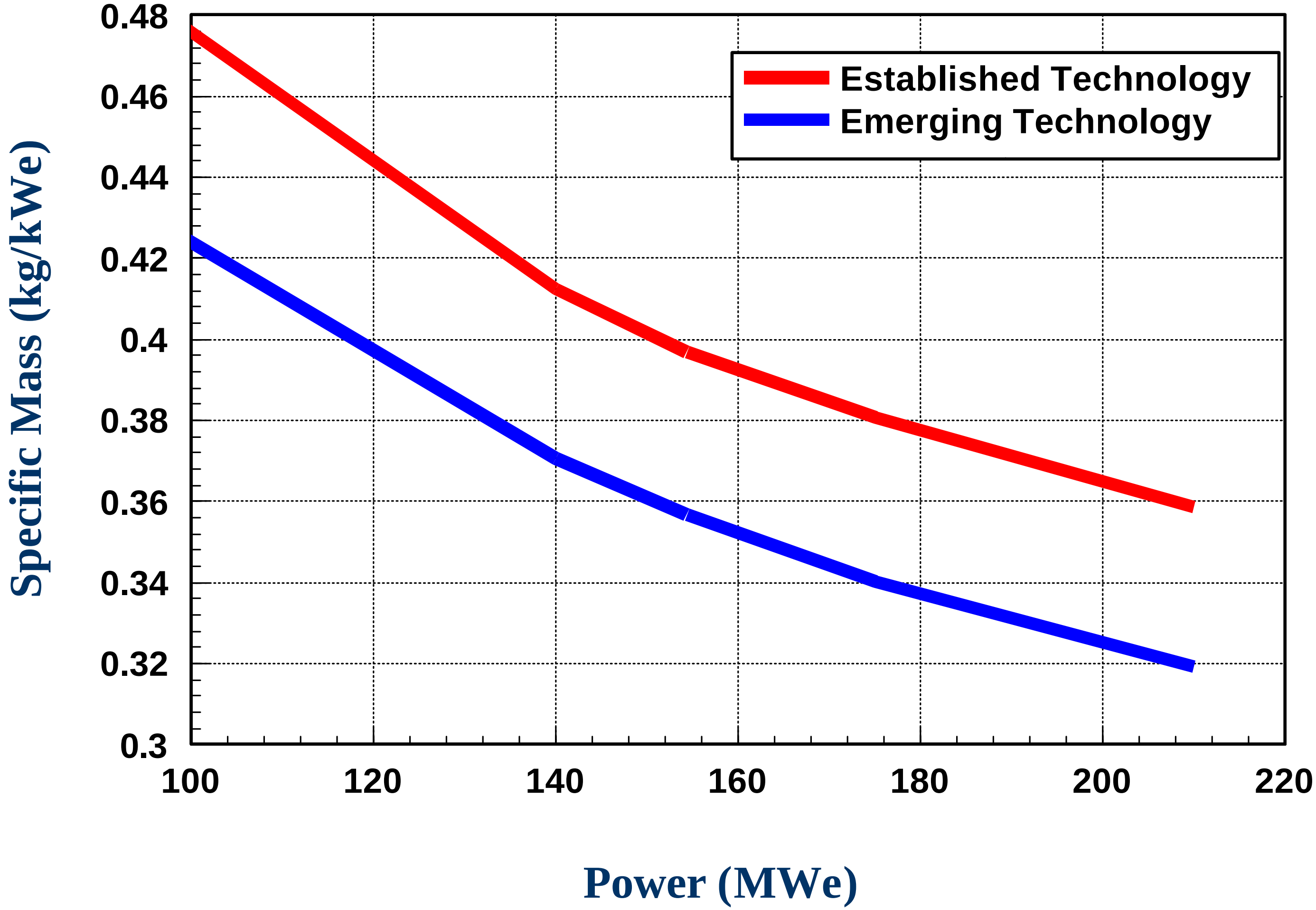
Fissioning Plasma Core Reactor
Weight Performance (<0.5 kg/kWe for >100 MWe)



Specific Mass Estimates Utilizing Advanced/Emerging Technologies

Power (MWe)	21	40	60	80	100	200
Reactor (MT)	7.77	10.23	12.26	14.11	15.75	22.42
Shield (MT)	5.30	6.52	7.65	8.78	9.86	14.98
Radiators (MT)	0.54	1.01	1.50	2.02	2.53	5.05
Structural (MT)	1.46	1.99	2.45	2.87	3.25	4.81
Pumps (MT)	0.66	1.23	1.84	2.46	3.09	6.16
MHD Gen. (MT)	3.00	3.72	4.24	4.68	5.05	6.36
Total (MT)	18.73	24.69	29.94	34.92	39.52	59.78
Sp. Mass (kg/kWe)	0.89	0.62	0.50	0.44	0.39	0.30

Fissioning Plasma Core Reactor Weight Performance

Core Volume 3.0 m^3						
Power/Core Pressure	210 MWe / Pcore=40 atm.			151 MWe / Pcore=30 atm.		
	Current Established	Current Advanced	Emerging Technology	Current Established	Current Advanced	Emerging Technology
Reactor (MT)	22.9	22.9	22.9	22.9	22.9	22.9
Shield (MT)	15.4	15.4	15.4	15.4	15.4	15.4
Radiators (MT)	23.4	15.7	15.7	17.6	11.8	11.8
Vessel/Struct. (MT)	7.1	4.9	4.5	7.1	4.9	4.5
Pumps (MT)	1.72	1.72	1.72	1.36	1.36	1.36
MHD Gen. (MT)	6.46	6.46	6.46	5.79	5.79	5.79
Total mass (MT)	77.1	67.2	66.8	70.2	62.2	61.8
Specific Mass (kg/kWe)	0.367	0.32	0.318	0.465	0.412	0.410

Fissioning Plasma Core Reactor Weight Performance

Core Volume 2.5 m^3						
Power/Core Pressure	175 MWe / Pcore=40 atm.			126 MWe / Pcore=30 atm.		
	Current Established	Current Advanced	Emerging Technology	Current Established	Current Advanced	Emerging Technology
Reactor (MT)	20.9	20.9	20.9	20.9	20.9	20.9
Shield (MT)	13.7	13.7	13.7	13.7	13.7	13.7
Radiators (MT)	19.5	13.1	13.1	14.6	9.8	9.8
Vessel/Struct. (MT)	6.4	4.5	4.1	6.4	4.5	4.1
Pumps (MT)	1.48	1.48	1.48	1.18	1.18	1.18
MHD Gen. (MT)	6.08	6.08	6.08	5.45	5.45	5.45
Total mass (MT)	68.1	59.7	59.3	62.3	55.5	55.2
Specific Mass (kg/kWe)	0.389	0.341	0.339	0.495	0.441	0.438

Fissioning Plasma Core Reactor Weight Performance

Core Volume 2.0 m^3						
Power/Core Pressure	140 MWe / Pcore=40 atm.			101 MWe / Pcore=30 atm.		
	Current Established	Current Advanced	Emerging Technology	Current Established	Current Advanced	Emerging Technology
Reactor (MT)	18.8	18.8	18.8	18.8	18.8	18.8
Shield (MT)	12.0	12.0	12.0	12.0	12.0	12.0
Radiators (MT)	15.6	10.4	10.4	11.8	7.9	7.9
Vessel/Struct. (MT)	5.8	3.9	3.6	5.8	3.9	3.6
Pumps (MT)	1.24	1.24	1.24	1.01	1.01	1.01
MHD Gen. (MT)	5.64	5.64	5.64	5.06	5.06	5.06
Total mass (MT)	59.0	52.0	51.7	54.4	48.7	48.4
Specific Mass (kg/kWe)	0.421	0.372	0.370	0.538	0.482	0.479

Summary

- VCR-MHD gives *direct* energy conversion at highest quality.
- MHD takes advantage of non-equilibrium ionization.

- Vapor Core @ High or Ultrahigh Temperature, meaning…
- Less costly radiators for heat rejection.

- Combined VCR-MHD space power might have very low specific mass, $M_{sp} \approx 0.5$ kg/kW$_e$.
- A magnetoplasmadynamic rocket can achieve high specific impulse, $I_{sp} \approx 10{,}000$ s.

- VASIMR propelled craft would need 100's of Megawatts — a VCR-MHD power supply can deliver.
- VASIMR has variable I_{sp} allowing for flexible abort scenarios.

Summary in Brief

- Direct energy conversion — Highest Quality.
- Low specific mass, M_{sp}.
- High specific impulse, I_{sp}.
- VCR-MHD power matching with VASIMR.
- Most materials are available.